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Review: A New Prospect of Streaming Potential Measurement in Alkaline-Surfactant-Polymer Flooding

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The synergy of alkaline, surfactant and polymer has revealed the potential of alkaline-surfactant-polymer (ASP) flooding as the most promising chemical Enhanced Oil Recovery (EOR) method. The synergistic interactions between the chemicals with reservoir rock and fluids could change the environment in porous media, which have potential effects on streaming potential measurement. Limited studies have been focused on the application of streaming potential in monitoring EOR processes, particularly ASP. This paper aims to propose the potential of streaming potential as a new prospect in monitoring ASP flooding by reviewing the streaming potential principles and associated ASP mechanisms. ASP mechanisms involve interfacial tension (IFT) reduction, mobility ratio improvement, and wettability alteration, which could enhance sweep efficiency and displacement process. The potential problem is the chemical losses due to polymer and surfactant adsorptions on the rock surfaces, but alkaline has significant advantage in reducing adsorption. The alteration of rock surface and fluid properties during ASP flooding could significantly affect streaming potential, which arises when the double layers exist with respect to the flow of excess charges in porous media. Streaming potential measurement should be further investigated to monitor the polymer and surfactant adsorption and ASP progression in porous media. Development of numerical model for the correlation would be a great advantage. The findings could provide new prospect in the correlation between streaming potential and ASP flooding, which could be a potential approach in monitoring the efficiency of the process during production.

1. Introduction

Effective downhole monitoring is critical to ensure the efficiency of the displacement process in recovering the oil. Among the current methods, measurement of streaming potential using electrodes permanently installed downhole has been a promising reservoir-monitoring technology (Jackson et al., 2005). Jaafar et al. (2009) have measured the streaming potential coupling coefficient in sandstones saturated with brine of higher salinity and reported the values of streaming potential coupling coefficient could potentially vary with rock texture or mineralogy, injected and formation brine salinity. Jackson et al. (2011) found that water encroaching on a production well causes changes in the streaming potential at the well while the water is several tens to hundreds of meters away. The contrast it has with most other downhole monitoring techniques, provides great advantages in monitoring the efficiency of secondary or tertiary recovery processes. Jaafar et al. (2013) found the point of zero charge (PZC) of two types of carbonate and sandstone core samples, where the voltage difference was measured at different pH of solution. Walker et al. (2014) applied new pressure transient approach as a faster approach than the conventional measurement methods, where the measured streaming potential coupling coefficients and zeta potential were aligned with the findings by Vinogradov et al. (2010) at high salinity. Results obtained by Esmaeili et al. (2016) agreed with the published experimental data, in fact much lower scattering in the data points was achieved for different saline injecting water. Streaming potential also changes with the wetting state of the rock surface. When the wettability of rock partially changes to the oil-wet, the overall zeta potential and coupling coefficient approach to their values of completely oil-wet sand particles (Sadeqi-

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Moqadam et al., 2016). Surfactant has the ability to reduce IFT, as well as changing the wetting state of the rock surface, which require further studies on the influences to the streaming potential.
Oil recovery efficiency depends on the original rock surface properties and its alteration during the EOR process, which occur with any changes of the fluids properties (Schramm et al., 1991). ASP provides synergy of alkaline, surfactant and polymer (Sheng, 2013) and the mechanisms include IFT reduction, wettability alteration, mobility ratio improvement (Sheng, 2011), which could improve sweep efficiency. The potential problem is the chemical losses due to polymer and surfactant adsorptions on the rock surfaces, but alkaline has significant advantage in reducing adsorption (Dang et al., 2011). These mechanisms should be well understood, since they have significant effects on streaming potential behaviour. Zeta potential is an important parameter in characterising the surface properties, and could be estimated using streaming potential measurement (Chen et al., 2014). There were no further studies from the past researchers on how streaming potential behaves and its significant uncertainties when ASP alters the properties of porous media. This paper aims is to propose the potential of streaming potential in monitoring ASP flooding by reviewing the streaming potential principles and associated ASP mechanisms. This could provide new knowledge and prospect in the correlation between streaming potential and ASP flooding for an efficient monitoring.

2. Streaming potential theory and measurement

Electrokinetic is a group of physicochemical phenomena, which involves the transport of charge, action of charged particle, effect of applied electrical potential and fluid transport in porous media to achieve a desired fluid flow or migration. Streaming potential, electroosmosis, electrophoresis, ion migration and electroviscosity are such phenomena included. Streaming potential arises as a result of electric current generated whenever an electrolyte moves with respect to a stationary solid that it is in contact with, as in a case water flows through earth and rock (Wurmstich et al., 1991). The mechanism of streaming potential is fluid flow in porous media producing the electric conduction current which flow in reverse direction through both liquids and solid matrix (Jackson et al., 2012). The conduction current acts to cancel the convection current in a steady state. Solid matrix that electrically conductive in any degree will reduce the magnitude of the streaming potential. Since streaming potential measurement has been used to estimate an average zeta potential of reservoir rock (Chen et al., 2014), any factors affecting zeta potential would have significant impact on the streaming potential measurement. According to Kirby and Jr (2004), zeta potential is dependent on cation concentration, buffer and cation type, pH, cation valency, and temperature. Streaming potential has shown good potential in monitoring wettability alteration (Jackson and Vinogradov, 2012) and behaves differently at high and low salinity condition (Vinogradov et al., 2010). The coupling coefficient could potentially vary with rock texture or mineralogy (Jaafar et al., 2009). The streaming potential behaviour could be related to all these factors for potential application in monitoring ASP flooding. Basic mathematical concept to understand the streaming potential is shown in Eq(1) (Sill, 1983). The coupling coefficient (C) relates the fluid (∇P) and electrical (∇V) potential gradients when the total current density (j) is zero.

$$C = \left.\frac{\partial V}{\partial P}\right|_{j=0} \tag{1}$$

Hunter (1981) has generated a relationship for the coupling coefficient as a function of the electrical conductivity of the brine (σ_w) and brine-saturated rock (σ_{rw}), permittivity (ε_w) and viscosity (μ_w) of the brine, and the zeta potential (ζ), as expressed in Eq(2).

$$C = \frac{\varepsilon_w \zeta}{\mu_w \sigma_{rw} F} \tag{2}$$

F is the formation factor (σ_w/σ_{rw}) measured when surface conductivity is negligible (associated with very saline brine). The magnitude of the streaming potential is dependent on the resistance of the return current path. Understanding of subsurface resistivity distribution will significantly assist in the shape and magnitude of streaming potential anomalies.

3. Electrical double layer (EDL) and zeta potential

EDL is a very important factor in electrokinetic phenomena. EDL which forms at solid-fluid interface is the origin of streaming potentials in porous media. A fundamental of understanding the physical properties of EDL is zeta potential which can be defined as electrical potential in electrolyte. A simple model describing the potential distribution in EDL is illustrated in Figure 1. The EDL is divided into a stagnant layer known as the stern layer and the diffuse layer. The slipping (shear) plane is defined as the point where the liquids begin to flow in a small distance from the solid surface. By definition, zeta potential (ζ) is the electrical potential at this shear plane. Zeta potential is directly proportional to the surface charge that developed on the solid surface when it is in contact with electrolyte (Luong and Sprik, 2014). However if the solid material already possesses a surface charge due to an imbalanced crystal structure, the two main chemical processes that act to develop a surface charge are the adsorption of ions and the hydrolysis of surface hydroxyl groups. Both processes typically occur simultaneously and depending on the chemical compositions of both the electrolyte and the solid. The chemistry at the interface can be treated by general chemical equilibrium equations and the equilibrium constants for many materials can be found in chemistry texts. The pH value of the electrolyte influences the surface charge and hence zeta potential in a solid and liquids chemical composition. The pH has a large effect on the hydrolysis of the surface hydroxyl group and lesser in ion adsorption (Zhang et al., 2015). By chemical equilibrium equation, the surface charge density decreases with increasing pH, resulting in decrease of the zeta potential.

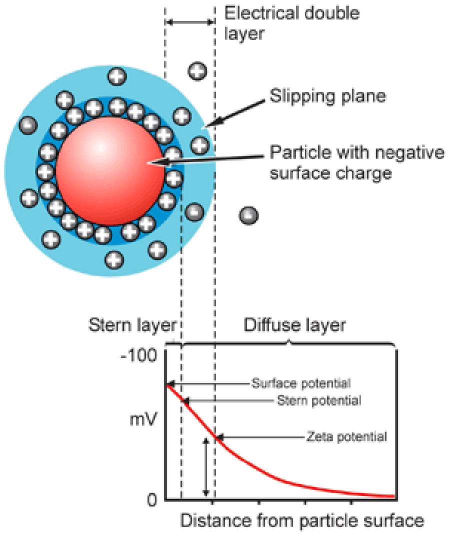

Figure 1: Schematic representation of zeta potential (Chilingar et al., 2014).

4. Alkaline-Surfactant-Polymer (ASP) flooding

ASP flooding is a chemical EOR process which involves the injection of surfactant, alkaline and polymer into an oil reservoir to produce the remaining residual oil, which could not be recovered by conventional water flood (Austine et al., 2015). Minimum facilities are required to add chemicals since most of the oil fields have been under water flooding, favouring the implementation of chemical EOR method (Sheng, 2013). ASP flooding is associated with several processes in enhancing oil recovery, including IFT reduction between trapped oil phase and ASP slug (Austine et al., 2015), improving mobility control and sweep efficiency as well as wettability reversal by surfactant to more favourable state (Shen et al., 2009).

4.1 Mechanisms of alkaline flooding

The injected alkaline or caustic solutions react with the natural acids (naphthenic acids) in the crude oils to form surfactants in-situ (sodium naphthenate), which act similarly with injected synthetic surfactants to reduce the IFT between oil/water (Olajire, 2014). This generated surfactant is referred as soap to differentiate it from the injected synthetic surfactant. The reaction equation is as follows (Sheng, 2013):

$$\mathrm{HA} + \mathrm{OH}^- \rightarrow \mathrm{A}^- + \mathrm{H_2O} \tag{3}$$

Where HA is a pseudo-acid component and A^- is the soap component. In ASP process, alkali has significant role in reducing the adsorption of surfactant on the grain surfaces through the formation and sequestering of divalent ions. Less surfactant injection is required, which ensures the surfactant to work more efficiently. Total Acid Number (TAN) of the oil affects how the alkali works in ASP flooding. Nelson et al. (1984) found the reduction of oil/water IFT during alkaline injection for oil with high TAN due to the combination effects of the generated soap with the injected surfactant. Alkali can still significantly reduce surfactant adsorption for oil with low TAN (Southwick et al., 2014). Liu et al. (2008) has proved that soap-to-surfactant ratio is important, which significantly contributed to the understanding of ASP process. Formation wettability can be altered with the presence of alkali to be either more water-wet or oil-wet. Other mechanisms involved include emulsification, oil entrainment and bubble entrapment.

4.2 Mechanisms of surfactant flooding

The surfactant flooding aims to recover the capillary-trapped residual oil which could not be produced during conventional water flooding. The key mechanism of surfactant flooding is the IFT reduction between oil and water, which aid in mobilising the residual oil. The higher the capillary number, the lower residual oil saturation (Stegemeier, 1977). Increase in capillary number can be achieved by increasing the injection fluid velocity and viscosity, as well reducing the IFT. IFT reduction is the most favourable and practical method, where IFT between a surfactant solution and oil can be reduced from 20 - 30 to 10^{-3} mN/m. Crude oil contains organic acid and salts, alcohols and other natural surface-active agents. When the crude oil is in contact with brine or water, an adsorbed film is formed by the accumulation of natural surfactants at the interface, which reduces the IFT of the crude oil/water interface (Olajire, 2014).

4.3 Mechanisms of polymer flooding

In polymer flooding, polymer is added to the waterflood to reduce the mobility. Polymer increases the viscosity of the aqueous phase as well as reducing water permeability due to mechanical entrapment, resulting in more favorable mobility ratio. With a more viscous phase, a more stable displacement can be achieved favouring the movement of the oil through the reservoir into the producing well, thus improving the sweep efficiency (Sorbie, 1991). A 5 % incremental recovery factor of OOIP (original oil in place) or more has been reported as a successful polymer flooding application (Rai et al., 2012). Due to polymer viscoelastic properties, polymer exerts a larger pull force on oil droplets or oil films, which reduces residual oil saturation (Wang et al., 2000).

4.4 Mechanisms and synergy in ASP

The alkali-surfactant mixture forms an emulsion with the oil, which is then displaced from the reservoir using a polymer drive. ASP flooding reduces the IFT between water and oil through the addition of surfactant, where the mobility ratio is further improved by the addition of polymer, resulting in improving displacement (Hirasaki et al., 2011). Addition of alkali to the water could reduce surfactant adsorption onto the rock surface to ensure minimum IFT and rock wettability alteration (Wang et al., 2015). Alkali reacts with crude oil to generate soap. An important mechanism in ASP is the synergy between in situ generated soap and synthetic surfactant. Generally, the optimum salinity for the soap is low, while the optimum salinity for the surfactant is high. The salinity range in which IFT reaches its low values is increased when they are functioning together (Sorbie, 1991). Addition of polymer reduces surfactant adsorption, or vice versa, as there is an adsorption competition between polymer and surfactant (Wang et al., 2015), besides improving sweep efficiency of alkaline and surfactants (Sheng, 2013). The decrease of liquid production was not only due to increase of the displacing fluid viscosity, but also related to emulsification and scaling after injection of ASP slug (Zhu et al., 2012). In conclusion, alkali and surfactant will produce synergistic IFT reduction while polymer improves sweep efficiency by emulsions (Sheng, 2011).

5. Potential of streaming potential measurement in monitoring ASP flooding

Many studies have been conducted to measure streaming potential related to groundwater movement and hydrocarbon production. Oil recovery efficiency depends on the original rock surface properties and its alteration during the EOR process, which occur with any changes of the fluids properties (Schramm et al., 1991). Streaming potential measurement has been a promising reservoir monitoring technique, but many studies have focused on water flooding brine-saturated porous media and the recent analysis of streaming potential at varying brine salinity. Limited studies have been conducted to measure streaming potential in monitoring EOR processes, such as water alternate gas (WAG) investigated by Anuar et al. (2013) and foam assisted water alternate gas (FAWAG) studied by Omar et al. (2013). Their studies in 2014 found that the streaming potential behaviour could be correlated with the waterfront progression during WAG (Anuar et al., 2014) and also with foam stability during FAWAG (Omar et al., 2014).

There is a significant degree of uncertainty in the behaviour of streaming potential when the porous media changes due to ASP flooding. According to Sadeqi-Moqadam et al. (2016), IFT of oil/water interface declined considerably for aqueous solutions having pHs greater than 9, which is alkaline and could also be referred to surfactant. This IFT reduction can be related to pH, which significantly affects the zeta potential and streaming potential. Polymer could improve the mobility ratio; however polymer adsorption is the main contribution for polymer losing during polymer flooding process. Dang et al. (2011) reported that polymer and surfactant adsorptions on the rock surfaces have been the main problem, but alkaline could significantly reduce the adsorption (Dang et al., 2011). In ASP, addition of polymer reduces surfactant adsorption, or vice versa (Wang et al., 2015), which influences the excess charge transported by the flow, thus affecting the streaming potential measurement. The synergistic interactions between the chemicals with the reservoir fluids and the rock surface could enhance the oil recovery (Austine et al., 2015). ASP flooding could alter the rock surface and fluid properties, which change the excess charge carried with the flow, affecting the streaming potential measurement. Streaming potential measurement should be further investigated to monitor the polymer and surfactant adsorption and ASP progression in porous media more efficiently. Development of numerical model for the correlation would be a great advantage in predicting the streaming potential signal measured during ASP flooding.

6. Conclusion

ASP flooding is the most promising chemical EOR method since it has the synergy of alkaline, surfactant and polymer. ASP mechanisms involve interfacial tension (IFT) reduction, mobility ratio improvement, and wettability alteration, which could enhance sweep efficiency and displacement process. The potential problem is the chemical losses due to polymer and surfactant adsorptions on the rock surfaces, but alkaline has significant advantage in reducing adsorption. ASP flooding could alter the rock surface and fluid properties which substantially affect streaming potential measurement. Streaming potential measurement should be further investigated to monitor the adsorptions and ASP progression in porous media more efficiently. Development of numerical model for the correlation would be a great advantage and the application in the real field could benefit the oil industry in term of making the EOR process more efficient and economic.

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